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NASA Case No. LAR-13563-1
Print Figure 3

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Serial No. 07/608,494
Filed Date November 2, 1990

(NASA-Case-LAR-13563-1) PASSIVE LAMINAR FLOW CONTROL OF CROSSFLOW VORTICITY Patent Application (NASA) 18 p CSCL 20D

N91-23410

Unclas

AWARDS ABSTRACT LAR-13563-1

PASSIVE LAMINAR FLOW CONTROL OF CROSSFLOW VORTICITY

This invention is directed to passive laminar flow control of crossflow vortices. In particular, the invention is an aerodynamic or hydrodynamic surface having geometric perturbations thereon.

FIG. 3 is an example of a riblet surface 3 having peaks 1 and valleys 2 for controlling passive laminar flow. FIG. 8 shows various other types of riblet surfaces which can be employed. The riblet surfaces have a predetermined spacing therebetween for controlling laminar flow by forcing the formation of crossflow vortices and minimizing amplification and growth of the vortices. In addition, longer runs of laminar flow can be achieved because the crossflow vortices which are forced to be present are those which do not grow enough to cause premature transition from laminar flow to turbulent flow, as shown in FIG. 4.

The invention provides greater simplicity, significant structural weight savings, lower cost, less volume, and less time for the design and operation of the laminar flow vehicle surface. The riblet surface is easier to maintain and repair, and more simple and less costly than active systems of laminar flow control. The technology required to manufacture riblet surfaces is in existence and is the same as that used to manufacture riblet surfaces which are employed to reduce skin friction in turbulent boundary layers.

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PASSIVE LAMINAR FLOW CONTROL OF CROSSFLOW VORTICITY

Origin of the Invention

The invention described herein was made by an employee of the United States Government and may be manufactered and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

Background of the Invention

1. Field of the Invention

The present invention is directed to reducing viscous or skin friction drag on aerodynamic or on hydrodynamic bodies. In particular, the present invention is directed to passive control of crossflow vorticity in laminar boundary layers. Passive control of crossflow vorticity is achieved by delaying transition of the laminar boundary layer to turbulence in three-dimensional boundary layers having crossflow instability.

2. Description of Related Art

Swept wing structures or non-axisymmetric bodies have three-dimensional laminar boundary layers. In these three-dimensional laminar boundary layers, the transition from laminar flow to turbulent flow can be initiated by any of five different modes of disturbance. Transition from laminar flow to turbulent flow on three-dimensional surfaces can result from inflectional instability in a free-shear layer across a laminar separation bubble, acoustic disturbances, roughness or waviness on the surface, catastrophic amplification of two-dimensional wavelike disturbances (Tollmien-Schlichting waves - see NACA-TR 909, Schubauer and Scramstad, 1948) or catastrophic amplification of three-dimensional disturbances (crossflow vorticity). Of the above-mentioned five modes of disturbance, crossflow on swept wings is the most difficult to control especially on aerodynamic and hydrodynamic surfaces.

Laminar flow is a highly streamlined flow in a viscous fluid near a solid boundary. Laminar flow can become turbulent flow, which is a fluid flow in which a velocity at a given point varies erratically in magnitude and direction, resulting from any of the five different modes of disturbance set forth above.

Crossflow vortices form in a laminar boundary layer as a result of spanwise or lateral pressure gradients causing a low momentum flow close to the surface in the boundary layer to move in a direction of reduced pressure. A higher momentum flow in an outer part of the boundary layer is not as affected by the lateral pressure gradients and maintains a flow direction substantially that of a freestream. The resulting three-dimensional velocity profile of the boundary is inflected, creating conditions necessary for the formation of vortices. These vortices are either moving or stationary. Theory indicates that wavelengths of crossflow vortices are amplified by any broad band of wavelength (vortex spacings). If conditions are not present to force a given spacing of the vortices to be within certain boundaries, naturally selected spacing (observed experimentally) will amplify very rapidly. The rapidly amplifying crossflow vortices occur in regions of rapidly falling pressures, for example, near the leading edge of a swept wing. It is believed that one mechanism by which crossflow vortices can affect laminar flow is by interacting with the two-dimensional wavelike disturbances (Tollmien-Schlichting waves), causing premature breakdown resulting in turbulence. Knowledge of boundary layer physics leads to understanding both the prior art and present invention control of the effects of crossflow vorticity.

The prior art employs passive means (i.e., pressure gradient means) and active means (i.e., suction, cooling or heating means) for controlling the effects of crossflow vorticity. Prior art passive control consists of limiting the magnitude and extent of lateral pressure gradients to preclude formation of crossflow vortices of sufficient strength to adversely affect boundary layer transition. On a wing, this is accomplished by limiting the sweep angle of the leading edge of the wing relative to the freestream, and by limiting the region of falling pressures to occur only near the leading edge. Thus, the growth of crossflow vortex strength is limited and longer runs of laminar flow are obtained.

Active means of laminar flow control in air incorporate suction and cooling systems. Active means of laminar flow control in water include heating the surface over which the boundary layer forms to provide control of the laminar instabilities. Suction, cooling, and heating systems favorably alter the three-dimensional laminar boundary layer velocity or density profiles such that the stability of the laminar flow is increased. These means also reduce the thickness of the boundary layer and the effective Reynolds number (the Reynolds number is represented by $R=(V/\upsilon) \times L$ - the ratio of velocity (V) to the kinematic viscosity of a fluid (υ) times the characteristic length (L) of a body (i.e., the chord of a wing equals the characteristic length)), thus improving the stability of the laminar flow. In addition, these methods reduce amplification of the Tollmien-Schlichting waves resulting in reduced adverse interaction between the crossflow vortices and the Tollmien-Schlichting waves, and producing longer runs of laminar flow.

A suction system provides very small slots or holes in the surface of a body. Suction is applied through these perforations and a quantity of the mass flow in the boundary layer is drawn into the body. The amount of suction required is calculated and controlled as a function of pressure gradient and Reynolds number (R). Power for the suction is provided by an auxiliary engine and pumping system. In a suction system, ducting is provided to carry suction air mass flow away from the body surfaces to a disposal location. The amount of heat required for hydrodynamic applications is also calculated and controlled as a function of pressure gradient and Reynolds number (R). In a heating system, heat is applied to the boundary layer through the solid surface of the body.

The above-mentioned systems provide a sufficient increase in the stability of laminar boundary layers so that an increase in the amount of laminar flow is achieved and significant reductions of the viscous drag on aerodynamic and hydrodynamic bodies is obtained.

Although the above-mentioned prior art systems increase the stability of laminar boundary layers, and therefore increase the amount of laminar flow, they have the disadvantages of having increased design and fabrication costs and limited performance of technology. The passive means whereby the sweep of a wing is limited, for example, significantly limits the ability of an airplane designer to minimize transonic drag. Increased wing sweep is used to increase the speed at which an airplane will experience increased drag resulting from the formation of shock waves. If maximum sweep is limited to less than, for example, 20°, in order to passively control the effect of crossflow vorticity, then the speed or drag of the airplane at speeds faster than approximately M=.7 (where M is the mach number), is severely compromised. Thus, passive control by limiting sweep has serious performance disadvantages.

With respect to the active means of suction or boundary layer heating/cooling systems for laminar flow control, the manufacturing tolerance required for the slots or holes in a suction surface are very expensive compared to the manufacture of surfaces without perforations. In addition, active laminar flow control systems require power to operate. Thus, these power requirements must be subtracted from the total gain to determine the net improvement in fuel efficiency. In addition, the systems contain pumps, ducting, controls and related structures all of which incur weight penalties. The fuel required to carry the additional weight must also be subtracted from the total gain to determine the net benefit.

Other prior art devices such as those set forth in U.S. Patent 1,994,054, U.S. Patent 1,454,479, and U.S. Patent 4,354,648, include ribs or corrugations on an underside of a surface, a rear surface having teeth formed therein, and rod members which project into the air stream boundary layer, respectively, all controlling turbulence for the purpose of increasing lift. None of the prior art teaches a means to control laminar flow for the purpose of reducing drag. Rather, the prior art devices are sufficiently large to cause transition from laminar flow to turbulent flow, and thus, preclude any possibility of achieving laminar flow.

Summary of the Invention

It is an object of the present invention to provide means for controlling laminar flow for the purpose of reducing drag by lengthening the run of laminar flow.

Another object of the present invention is to provide a device which produces a desired variable effect on laminar flow stability without causing a transition from laminar flow to turbulent flow.

A further object of the present invention is to provide a device for controlling laminar flow which is relatively inexpensive, easy to fabricate and simple to maintain.

It is a further object of the present invention to provide laminar control which forces the selection of crossflow wavelengths so they do not amplify sufficiently to initiate transition to turbulent flow at design flight conditions.

Another object of the present invention is to provide laminar control which reduces aerodynamic heating of surfaces by increasing the lengths of regions of laminar flow resulting in significant structural weight savings.

To obtain the above-mentioned objects, the present invention comprises an aerodynamic or hydrodynamic surface having geometric perturbations thereon, the geometric perturbations comprising a riblet surface having grooves and peaks formed therein, the peaks having sharp, pointed tops for generating vortices in a direction of fluid flow.

The present invention also comprises a passive laminar flow control device, comprising an aerodynamic surface and perturbations formed in the aerodynamic surface having a desired spacing therebetween for minimizing the amplification and growth of crossflow vortices. The perturbations of the passive laminar flow control device are riblets formed on the aerodynamic surface, the riblets having peaks and grooves aligned approximately in a direction in which a fluid flows. The peaks have sharp tops for generating vortices in the direction of fluid flow. The spacing between the peaks is selected to generate vortices having a distance therebetween such that the vortices do not amplify rapidly. The spacing between the riblets can be selected to be less than one-half the distance at which a maximum amplified stationary vortex occurs. The spacing between the riblets is approximately between .002 and .05 inches. In addition, the spacing between the riblets can be at least more than twice the distance at which a maximum amplified stationary vortex occurs. That is, the spacing can be approximately between .05 and .10 inches. The riblets have a height less than that at which roughness effects in a laminar boundary layer near a leading edge of the riblet surface occur, and is less than approximately .002 inches. The riblets are located on the aerodynamic surface in a region of accelerated fluid flow.

Brief Description of the Drawings

FIG. 1A is a graph of a typical velocity component in two directions in which the boundary layer flows over, for example, an aerodynamic surface;

FIG. 1B is a typical inflected velocity profile of an aerodynamic surface;

FIG. 2 is a graph of the vorticity characteristics due to boundary layer crossflow vortices on the aerodynamic surface;

FIG. 3 is a riblet surface for a hydrodynamic or aerodynamic surface according to the present invention which includes grooves having peaks and valleys aligned in the fluid flow direction;

FIG. 4 is a graph of crossflow disturbance amplification ratio (n) at different wavelengths for stationary disturbances on an aerodynamic or hydrodynamic surface;

FIG. 5 is a top view of, for example, a wing, showing the orientation of a riblet surface, a direction of rotation of crossflow vortices, and a direction of rotation of riblet vortices, according to the present invention;

FIG. 6 is a graph of an airfoil profile, showing the pressure distribution and riblet surface location with respect to an aerodynamic suface;

FIG. 7 is a diagram of the vortices which are generated on the riblet surface of an aerodynamic surface; and

FIGS. 8A-8E are variations in the geometry of the riblet surface according to the present invention.

Description of the Preferred Embodiments

FIGS. 1A and 1B are diagrams of the velocity components in two directions (in a direction of external flow (a) and in a direction normal to the direction of external flow (b)) on a three-dimensional surface such as a wing or empennage having sweep, fuselages, or engine nacelles which are non-axisymmetric. The resultant velocity profile (c) in FIG. 1B is such that a vorticity (d) is formed in the boundary layer.

FIG. 2 is a top view of the vorticity which occurs due to boundary layer crossflow vortices which flow in a direction approximately into the paper. In a laminar boundary layer, these vortices grow in strength.

Eventually, a transition from laminar flow to turbulent flow occurs. Past experimental and theoretical studies indicate that stationary vortices or waves have been observed forming on surfaces of aircraft in flight having spacing between the waves of approximately 0.25 to 0.04 inches. A typical crossflow vortex spacing (λ) is approximately 3δ to 4δ where λ is the spacing (wavelength) and δ is the boundary layer thickness at a chordwise location where crossflow velocities are a maximum (i.e., near a leading edge of a swept wing). In addition, moving vortices or waves have been observed experimentally in wind tunnels and have been theoretically predicted. In experiments, the disturbance mode (vortex spacing/wavelength and frequency/motion) has been related to the boundary conditions of the test. The boundary conditions that determine which instability mode will develop include freestream turbulence and acoustic disturbances, and geometric perturbations on the surface over which the boundary layer flows.

The present invention includes geometric perturbations for any aerodynamic or hydrodynamic surface. The purpose of the perturbations are to force the formation of crossflow vortices having a desired spacing which will minimize amplification or growth of the vortices. Thus, longer runs of laminar flow can be achieved because the crossflow vortices, which are forcibly present, do not grow rapidly enough to cause premature transition from laminar flow to turbulent flow.

A particular embodiment of the invention includes a riblet surface having grooves with peaks 1 and valleys 2 aligned approximately in a streamwise direction, as shown in FIG. 3. The effect that the riblet surface 3 has with respect to the growth of crossflow vortices at different wavelengths for stationary disturbances is shown in FIG. 4. The ordinate indicates the amplification of the crossflow vortices (n) and the abscissa indicates the crossflow vortex spacing or wavelength (λ). The maximum amplification (that is, the most rapid growth) of the crossflow vortices occurs at a selected wavelength (a). At other wavelengths (b), the amplification of crossflow vortices is greatly reduced. Thus, the present invention forces the formation of vortices in the laminar boundary layer at spacings (wavelengths) which will not amplify as rapidly as the most amplified spacing 4 illustrated in FIG. 3.

The alignment of the riblet peaks 1 is arranged such that the local boundary layer flow direction creates vorticity with the same approximate streamline orientation as that of the naturally occurring crossflow vortices. The riblet height 5 is shown in FIG. 3 as is the flow direction 6.

FIG. 5 is a diagram of a swept wing 8 having natural crossflow vortices as shown by (a) and vortices on the riblet surface 3 as shown by (b). The spacing 4 between the peaks 1 shown in FIG. 3 is selected by design to generate vortices having spacing different than that which amplifies most rapidly. The selection of the riblet spacing 4 can be determined by standard computational methods. Employing such methods, the most amplified stationary vortex spacing is determined as shown in FIG. 4. The riblet spacing 4 is then selected to be much smaller or much larger than the most amplified spacing.

Riblet spacing 4 of less than one-half or more than twice the most amplified spacing may be sufficient for satisfactory riblet performance. Typically spacings for many subsonic airplane applications will range between 0.002 and 0.10 inches. The riblet height 5 (FIG. 3) is required to be smaller than that which can cause significant roughness effects in the laminar boundary layer at a location near the leading edge 7 where the riblet surface 3 is installed. In subsonic applications, for example, the riblet height 5 is less than 0.02 inches.

On active laminar flow control surfaces (i.e., suction or heating/cooling means) riblets provide a means to reduce the power required for the active control system. This is because the riblets create vortex wavelengths which amplify so slowly that smaller suction mass flow (or heating or cooling rates) are required to achieve desired levels of laminar flow stability.

Typically, a riblet surface on a subsonic, supersonic, or hypersonic swept wing will be in regions of accelerated flow as shown in FIG. 6 (i.e., the coefficient of pressure is greater than 1 and the chordwise location is approximately .2). On a swept wing, a riblet surface will begin at the leading edge upstream of the location where crossflow first begins to amplify. The riblet surface may be wrapped around the leading edge in some circumstances, continuing to maintain streamwise alignment of the riblet peaks and valleys. Alignment of riblets in the streamwise direction causes the formation of vortices at the peaks 1 of the riblets as shown in FIG. 7. Because of the persistent nature of vorticity in fluid flow, the vortex spacing created by the riblet surface 3 will tend to persist in a chordwise direction as the boundary level develops. In addition, the forced vortex spacing will be reinforced over the chordwise extent of the riblet surface 3. Thus, for some swept wing applications, a riblet surface will be employed over as much as 60% of the air foil chord. In other applications, riblet surfaces can be distributed in regions where crossflow vorticity is expected to amplify.

Other embodiments of the invention include variations in the detailed geometry of the riblet surface 3. These geometric variations can include, but are not limited to, the arrangements shown in FIGS. 8A-8E. Further embodiments include any surface geometry which creates a vorticity field having characteristic wavelengths different from the wavelengths of naturally occurring crossflow vortices. The detailed geometry of the riblet surface creates lengthened runs of laminar flow, thus reducing viscous drag. The riblets also create boundary conditions for fluid flow which forces the selection of crossflow wavelengths which do not amplify sufficiently to initiate the transition to turbulent flow within regions of accelerating flow at design flight conditions. In certain applications, riblet spacing 4 can be selected to reduce the amplification of crossflow vorticity sufficiently to reduce the requirement for suction, heating or cooling, in active laminar flow control applications. For supersonic and hypersonic applications, the riblet surface reduces the aerodynamic heating of the surfaces by increasing the length of the regions of laminar flow resulting in significant structural weight savings. Further, riblet surfaces provide a unique passive system for stabilizing crossflow disturbance growth in three-dimensional laminar boundary layers. The limitations of both active and passive systems of laminar flow control are circumvented while maintaining simplicity, reducing weight, cost, volume, and the time required for design and operation of laminar flow surfaces. The maintainability and repairability of riblet surfaces is more simple and less costly than active systems of laminar flow control. The technology required to manufacture riblet surfaces is in existence and is the same technology used to manufacture riblet surfaces for reducing skin friction in turbulent boundary layers. Therefore, new manufacturing technology for the riblets is not required.

The invention provides a passive system for laminar flow control for stabilizing crossflow vorticity disturbance growth in three-dimensional laminar boundary layers. The riblet surface 3 set forth above is a passive system for delaying laminar boundary layer transition from laminar flow to turbulent flow in three-dimensional boundary layers where crossflow instability is present. Further, the passive system of this invention reduces the suction mass flow or heating or cooling power requirements which are necessary for active laminar flow control systems.

The foregoing is considered as illustrative only of the principles of the invention. Further, since numerous modifications and changes will readily occur to those skilled in the art, it is not desired to limit the invention to the exact construction and applications shown and described, and accordingly, all suitable modifications and equivalents may be resorted to, falling within the scope of the invention and the appended claims and their equivalents.

What is claimed is:

PASSIVE LAMINAR FLOW CONTROL OF CROSSFLOW VORTICITY

Abstract of the Disclosure

A passive laminar flow crossflow vorticity control system includes an aerodynamic or hydrodynamic surface having geometric perturbations. The perturbations include peaks and valleys having a predetermined spacing and aligned approximately in a streamline direction to force the formation of crossflow vortices. This minimizes amplification and growth of the vortices, thus delaying transition to turbulence and reducing overall drag.

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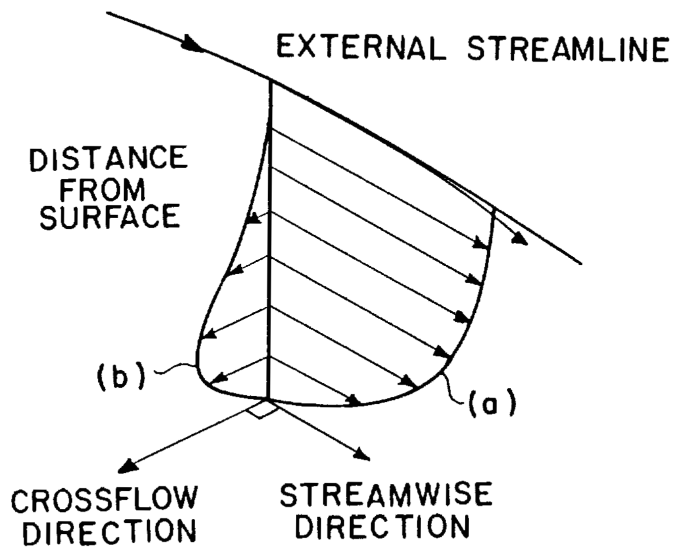

FIG. 1A

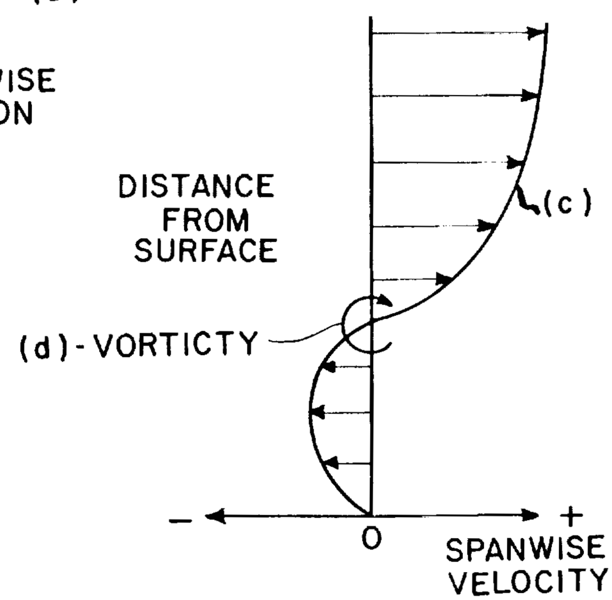

FIG. 1B

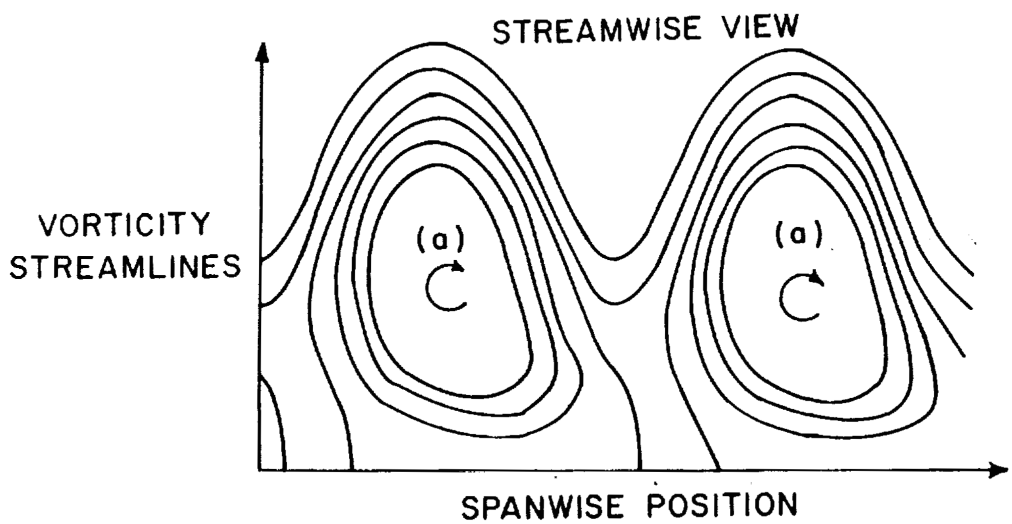

FIG. 2

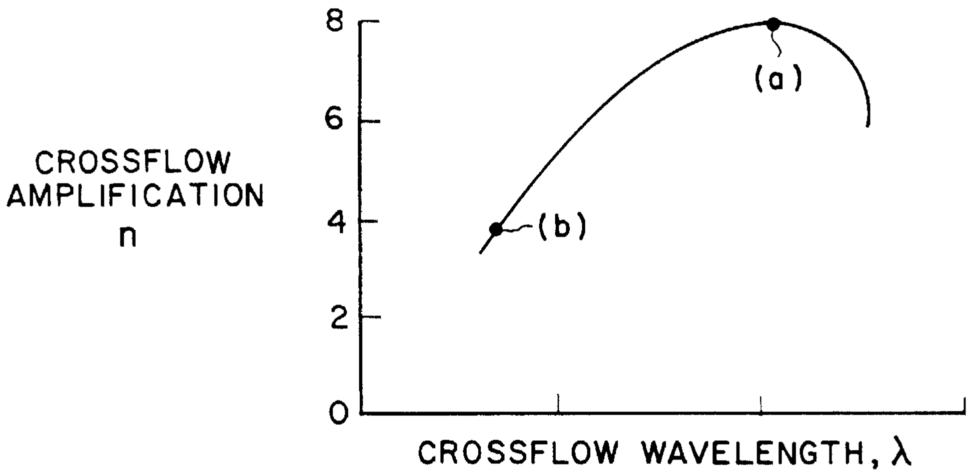
8
6
4
2
0
CROSSFLOW
AMPLIFICATION
n
(a)
(b)
CROSSFLOW WAVELENGTH, λ

FIG. 4

FIG. 3

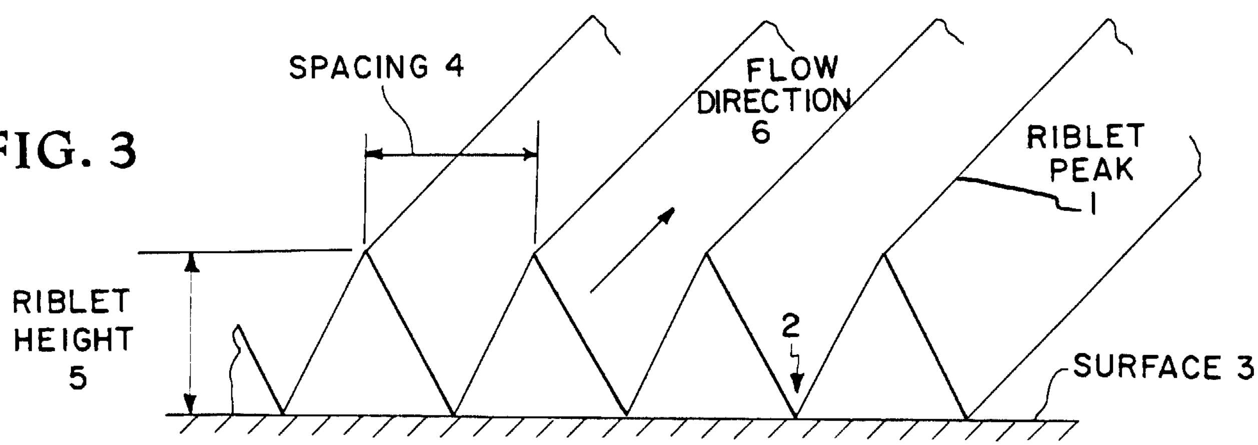
SPACING 4
FLOW
DIRECTION
6
RIBLET
PEAK
1
RIBLET
HEIGHT
5
2
SURFACE 3

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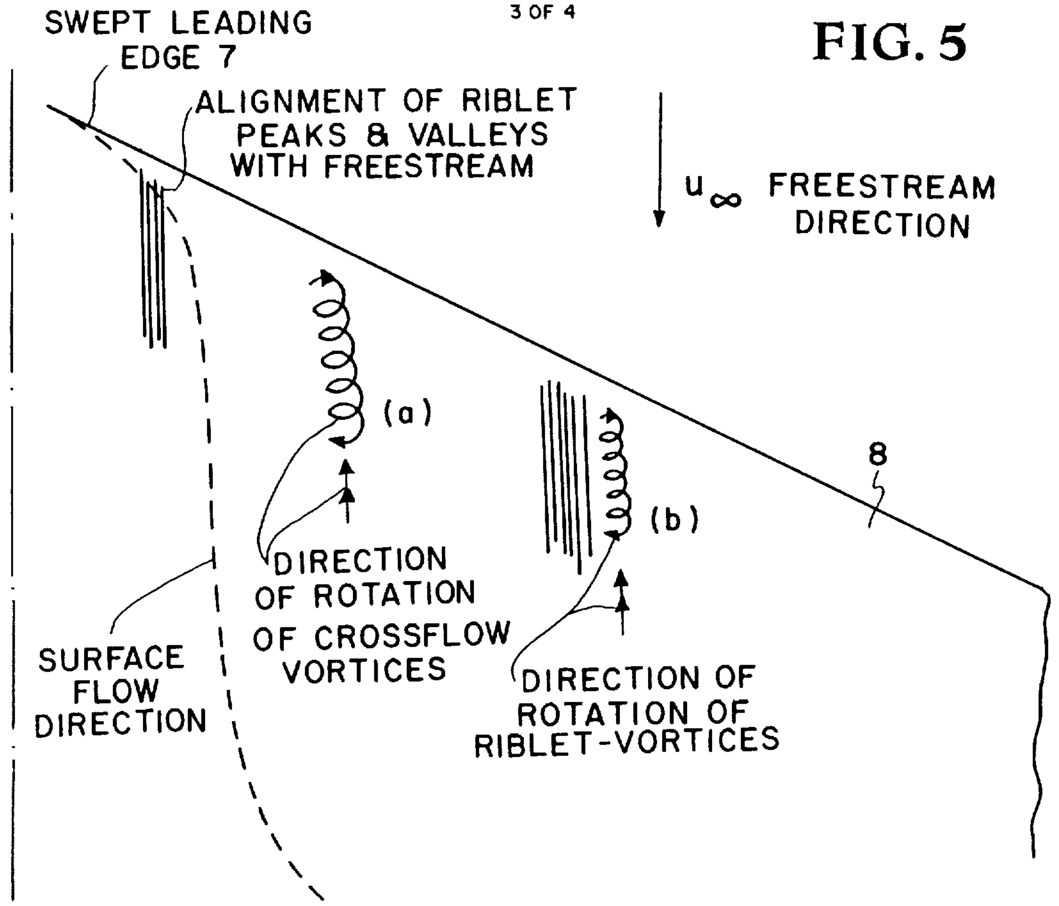
FIG. 5



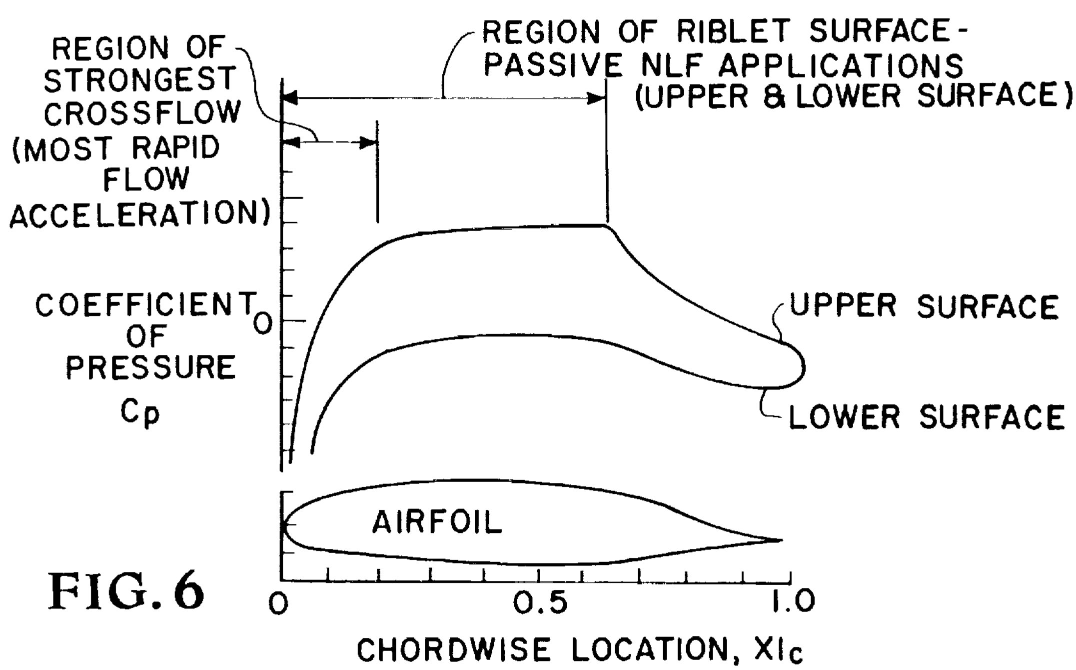


FIG. 6

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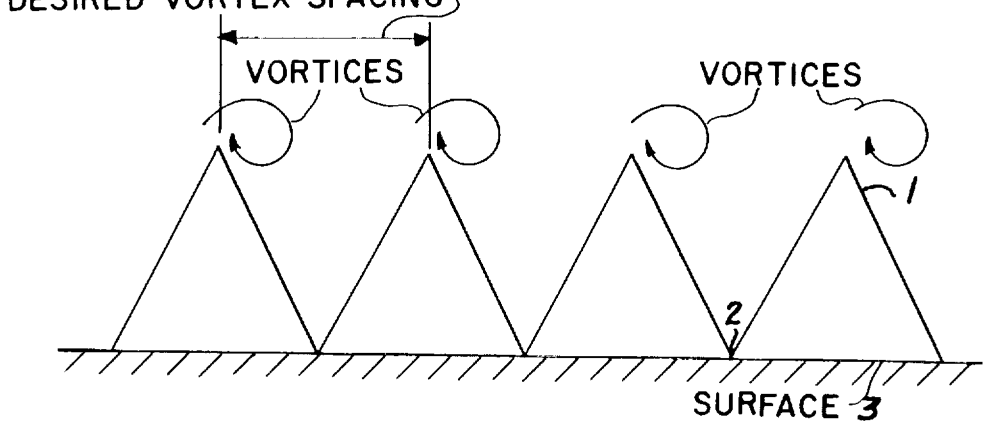

FIG. 7

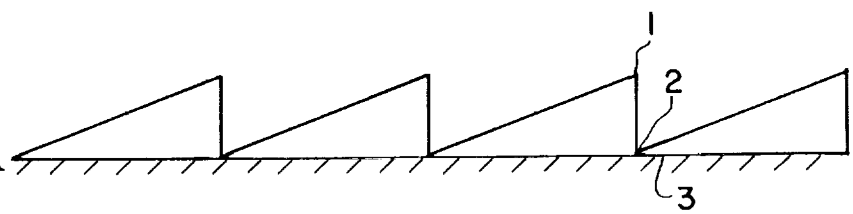

FIG. 8A

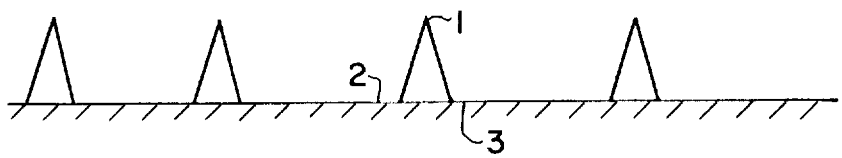

FIG. 8B

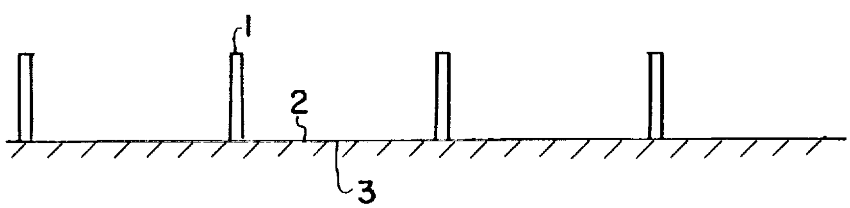

FIG. 8C

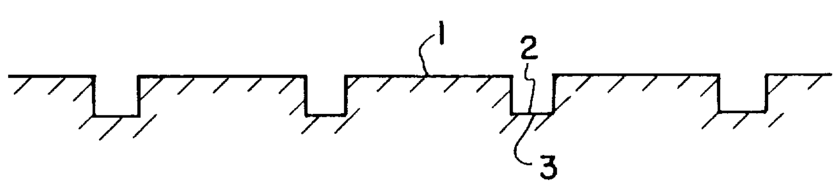

FIG. 8E

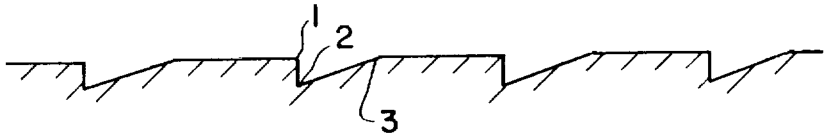

FIG. 8F